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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)


A new scheme for radar detection and discrimination, the radar waveform synthesis method, is investigated. This scheme consists of synthesizing the aspect-independent, incident radar signal which excites the target in such a way that the return radar signal contains only a single natural mode of the target in the late-time period. When the synthesized incident signal for a preselected target is applied to a wrong target, the return signal will be significantly different from the expected natural mode, thus, the wrong target


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An alternative scheme is also developed to extract the single-mode return signal by convolving, using a computer, the required incident radar signal for the single-mode excitation with a return radar signal from the target excited by an arbitrary incident radar signal.

A study on the synthesis of the K-pulse has been initiated. The progress on the experimental setup and study is reported.

RADAR WAVEFORM SYNTHESIS FOR TARGET IDENTIFICATION


## Abstract

A new scheme for radar detection and discrimination, the radar waveform synthesis method, is investigated. This scheme consists of synthesizing the aspect-independent, incident radar signal which excites the target in such a way that the return radar signal contains only a single natural mode of the target in the late-time period. When the synthesized incident signal for a preselected target is applied to a wrong target, the return signal will be significantly different from the expected natural mode, thus, the wrong target can be discriminated.

An alternative scheme is also developed to extract the single-mode return signal by convolving, using a computer, the required incident radar signal for the single-mode excitation with a return radar signal from the target excited by an arbitrary incident radar signal.

A study on the synthesis of the K-pulse has been initiated. The progress on the experimental setup and study is reported.

## 1. Introduction

The purpose of this research is to develop a new scheme of radar detection and discrimination. This scheme consists of synthesizing the aspect-independent, incident radar signal which excites the target in such a way that the return radar signal contains only a single natural mode of the target in the late-time period. When the synthesized incident signal for a preselected target is applied to a wrong target, the return signal will be significantly different from the expected natural mode, thus, the wrong target can be discriminated.

So far we have demonstrated the feasibility of this scheme for the wire target, the spherical target and the infinite-cylinder target. In each case, the required incident radar signals for various single-mode excitations were synthesized, and the return signals from the right target and wrong targets were obtained. We are in the process of analyzing the targets of two coupled-wires and an aircraft modeled with cylindrical elements.

One major progress was made during the course of our study. We have developed an alternative scheme of obtaining the single-mode return signal by convolving, using a computer, the required incident radar signal for the single-mode excitation with a return radar signal from the target excited by an arbitrary incident radar signal. This finding is significant because with this alternative scheme, it will not be necessary to generate and radiate the required incident radar signals for the single-mode excitation, which have quite complicated waveforms in some cases. Now, the required incident radar signals for the single-mode excitations are theoretically synthesized and stored in the computer. When these signals were convolved with the return signals from the targets illuminated by some convenient radar signals, the return signal from the right target produces a single natural mode output while that from the wrong target will not yield the expected natural mode. To test this alternative scheme, and before we produce our own experimental

results, some of experimental results on a spherical target supplied by Dr. Bruce Hollman were used for testing.

Recently we have also initiated the study on the K-pulse which is an aspect-independent incident radar signal which excites a target in such a way that it produces a return signal with zero late-time response.

We have also made good progress in the construction of the experimental setup and some preliminary results are discussed here.

## 2. Excitation of Single-Mode Backscatters with Synthesized Radar Signals

So far we have found that (1) for any radar target, there exists a unique, aspect independent waveform for the incident radar signal which can excite the target in such a way that the return signal from the target contains only a single natural mode of the target in its late-time period, (2) for a slender target, the required incident signal for the single-mode excitation has a simple waveform consisting mainly of a single-mode, while that for a fat target has a complicated waveform and composed of many natural modes, and (3) when the synthesized incident signal for exciting a particular natural mode of a preselected target is applied to a wrong target, the return signal will be significantly different from that of the expected natural mode, thus, the wrong target can be discriminated. Examples are given to explain these results.

Consider a wire target of length L and radius a such as shown in Figure 1. The aspect independent, required incident signals for exciting the first, the second and the third natural mode of the target in the late-time period of the return signal are shown in Figure 2. These waveforms have a duration of $\tau_e = 2.16\ (L/c)$ and consist mainly of the natural modes which are to be excited in the return signals. To show that these required incident signals are aspect independent, a numerical example is given. Figure 3 shows the return signals from the target oriented at various aspect angles, $\theta = 15°$, $45°$, $60°$, and $89°$, when the target is illuminated by the incident signal which is synthesized for the first-mode excitation. It is observed that the return signal for each

case of aspect angle remains that of the first natural mode, even though the amplitude and the phase angle vary with the aspect angle.

Figure 4 is used to demonstrate the capability of target discrimination possessed by this scheme. This figure shows the return signals from three targets, the right target (wire), a wire 5% longer than the right target and a wire 20% longer, when they are illuminated at 30° aspect angle by the incident signal which is synthesized for exciting the first natural mode of the right target. It is observed in Figure 4 that the return signal from the right target is a pure first natural mode; that from the 5% longer displays a slightly distorted waveform and a shifted frequency from that of the first natural mode of the right target; and that from the 20% longer target shows an irregular waveform. Based on these return signals, it is easy to discriminate the wrong target from the right target. More information on this subject for a wire target is available elsewhere [1].

Next, let's consider a fat target such as a sphere of radius as shown in Figure 5. The required incident signals for exciting various single-mode backscatters and resulting single-mode return signals are shown in Figures 6 and 7. Figure 6 shows the required incident signal for exciting the first-mode backscatter and the return signal which indeed shows the first natural mode in the late-time period. The duration of the required incident signal is set to be one period of the first natural mode, $\tau_e = 7.26\ (a/c)$. The waveform of the required incident signal is found to contain a rapidly oscillatory component in the initial stage. However, the return signal contains only the much slower varying, first natural mode in the late-time period. This phenomenon is different from the case of a thin wire where the required incident signal for single-mode excitation consists mainly of the wanted natural mode. The reason is that the natural modes of a thin wire are nearly orthogonal while that of a sphere are not orthogonal due to their large damping coefficients.

Figure 7 shows the required incident signal for exciting the third-mode backscatter and the return signal which contains only the third natural mode in the late-time period. The required incident signal has a duration of one period of the first natural mode, and its waveform consists of a rapidly oscillatory component superimposed on a slowly varying component. The return signal displays a pure third natural mode in its late-time period.

These two examples show that the required incident signal for exciting a single-mode backscatter from a fat target has a complicated waveform and composed of many natural modes. In fact, 21 natural mode of appropriate amplitude and phase angles were needed to construct the required incident signals for the first and the third mode excitation as that shown in Figures 6 and 7.

To show the capability of target discrimination of this method, a numerical example is given in Figure 8. Figure 8 shows the return signals from two spheres, the right sphere and a wrong sphere which radius is 10% smaller than that of the right sphere, when they are illuminated by the required incident signal for exciting the third-mode backscatter from the right sphere. It is observed that the return signal from the right sphere is a pure third natural mode while that from the wrong sphere exhibits an irregular waveform. From this example, it is evident that the wrong target can be discriminated from the right target if the incident signal is properly synthesized for single-mode excitation. More information on this subject concerning a spherical target is available [2].

Observing from the results of a fat target, it may be difficult to apply the radar waveform synthesis method to a fat target because of the complexity of the required incident signal for the single-mode excitation. The complex waveforms such as that shown in Figures 6 and 7 may be difficult to generate and radiate without distortion. To overcome this difficulty, an alternative scheme which should be useful in practice is discussed in Section 3.

## 3. Extraction of Single-Mode Backscatters from Arbitrary Radar Returns Using Synthesized Radar Signals

To avoid the necessity of generating and radiating those complex required incident signals for the single-mode excitations, we have developed an alternative scheme of obtaining the single-mode backscatters by convolving, using a computer, the required incident signal for the single-mode excitation with a return radar signal from the target which is excited by an arbitrary incident radar signal. The principle of this scheme is explained below.

Let's consider the two equivalent schemes for the target discrimination as depicted in Figure 9. The scheme in the left is the original radar waveform synthesis method: It sends out the required incident radar signal which is synthesized for the single-mode excitation, to the target. The right target will give a single-mode return signal but the wrong target will not. The scheme shown in the right is the alternative scheme: The required incident signal for the single-mode excitation is synthesized and stored in a computer. An incident radar signal with some convenient waveform is sent to the target, which will give a return signal with an irregular waveform. The return signal is fed into the computer and is convolved with that required incident signal stored in the computer. The output signal after the convolution will display a single natural mode of the target (a pure damped sinusoid) if the target is the right target; the return signal from the wrong target will not produce the expected natural mode after the convolution.

These two schemes shown in Figure 9 are completely equivalent. However, the alternative scheme has the advantage of not generating and radiating the required incident signal for the single-mode excitation; it is stored in the computer. Another advantage for the alternative scheme is that we can use any convenient existing radar pulse to illuminate the target as long as it produces a return signal which contains all the wanted natural modes of the target in its late-time response.

To test this alternative scheme, and before we produce our own experimental results, some of experimental results on a spherical target supplied by Dr. Bruce Hollmann were used for the testing. We have used the bistatic response of Hollmann's 5 inch (diameter) sphere because this sphere had the least deformation. The radar return used in the convolution is his bistatic response minus the clutter and is shown in Fig. 10. This radar return still contains a great deal of clutter and noise especially in the late-time period. The required radar signals for the first-mode excitation and the third-mode excitation are those shown in Figures 6 and 7, respectively. It is noted that those required radar signals were synthesized for exciting single-mode backscatters, and they may not be accurate for the bistatic response. However, even with these two discrepancies, using the contaminated bistatic response and the required radar signals for exciting single-mode backscatters, we have produced quite encouraging results as shown in Figures 11 and 12. Figure 11 shows the output signal produced by convolving the bistatic response of Figure 10 with the required radar signal for the first-mode excitation as shown in Figure 6. It is observed that the first natural mode is distinctly produced even though there are some noise present. This noise is expected since it is present in the bistatic response of Figure 10. Figure 12 shows the output signal produced by convolving the bistatic response of Figure 10 with the required radar signal for the third-mode excitation as shown in Figure 7. Again, the third natural mode is distinctly produced in the presence of some noise. We have also observed that if the radar returns of other targets were convolved with the required radar signals of Figures 6 and 7, the output signals become quite different from those natural modes shown in Figures 11 and 12.

These results are very preliminary, and we will make major efforts in pursuing this alternative scheme in the future.

## 4. *Theory for Extraction of Single-Mode Backscatters from Arbitrary Radar Returns Using Synthesized Radar Signals*

A simple theory behind the scheme of extracting the single-mode backscatters from arbitrary radar returns using synthesized radar signals is presented in this section.

Assuming that the late-time response of an arbitrary radar return is available from the measurement, and it consists of the sum of natural modes of the target as follows:

$$E^r(t) = \left[\sum_{n=1}^{N} a_n(\theta)\, e^{\sigma_n t} \cos(\omega_n t + \phi_n(\theta))\right] U(t) \tag{1}$$

where $E^r(t)$ is the radar return, $t=0$ is some reference time point in the late-time period, $a_n(\theta)$ and $\phi_n(\theta)$ are the aspect dependent amplitude and phase angle of the nth mode, $\sigma_n$ and $\omega_n$ are the aspect-independent damping factor and frequency of the nth natural mode, $U(t)$ is the step function, and N is the number of the natural modes to be considered. Theoretically N should be infinite but in practice it is finite because usual incident and return radar signals are frequency limited.

With $E^r(t)$ available, we aim to synthesize an excitation signal, $E^e(t)$, with a duration of $T_e$ in such a way that when $E^e(t)$ convolves with $E^r(t)$, it will produce a single-mode output signal, $E^o(\tau)$. Mathematically, it means

$$E^o(\tau) = \int_0^{T_e} E^e(t)\, E^r(\tau - t)\,dt = \text{single-mode} \tag{2}$$

We will assign a desired natural mode for $E^o(\tau)$ and an appropriate signal duration $T_e$ for $E^e(t)$, and then proceed to determine $E^e(t)$ from eq. (2). Substituting eq. (1) in eq. (2) gives

$$E^o(\tau) = \int_0^{T_e} E^e(t) \left[\sum_{n=1}^{N} a_n(\theta)\, e^{\sigma_n(\tau - t)} \cos(\omega_n(\tau - t) + \phi_n(\theta))\right] U(\tau - t)\,dt \tag{3}$$

Because of the step function $U(\tau-t)$, $E^{o}(\tau)$ has different expressions for the late-time period (of the output signal) of $\tau > T_e$ and the early-time period of $\tau < T_e$.

For $\tau > T_e$ (late-time),

$$E^{o}(\tau) = \int_0^{T_e} E^{e}(t)\,[\sum_{n=1}^{N} a_n(\theta)\, e^{\sigma_n(\tau-t)} \cos(\omega_n(\tau-t) + \phi_n(\theta))]dt$$

$$= \sum_{n=1}^{N} a_n(\theta)\, e^{\sigma_n \tau}[A_n \cos(\omega_n\tau + \phi_n(\theta)) + B_n \sin(\omega_n\tau + \phi_n(\theta))] \qquad (4)$$

where

$$A_n = \int_0^{T_e} E^{e}(t)\, e^{-\sigma_n \tau} \cos \omega_n t\, dt \qquad (5)$$

$$B_n = \int_0^{T_e} E^{e}(t)\, e^{-\sigma_n t} \sin \omega_n t\, dt \qquad (6)$$

Based on eqs. (4) to (6), we can synthesize an $E^{e}(t)$ in such a way that all the coefficients $A_n$ and $B_n$ vanish except $A_j$ or $B_j$. If so, the output signal $E^{o}(\tau)$ will contain only the jth natural mode. This kind of synthesis can not be performed for the early-time period of $\tau < T_e$ as explained below.

For $\tau < T_e$ (late-time),

$$E^{o}(\tau) = \int_0^{\tau} E^{e}(t)\,[\sum_{n=1}^{N} a_n(\theta)\, e^{\sigma_n(\tau-t)} \cos(\omega_n(\tau-t) + \phi_n(\theta))]dt$$

where the upper limit of the integration is changed from $T_e$ to $\tau$ because of $U(\tau-t)$ function in eq. (3). We then have

$$E^{o}(\tau) = \sum_{n=1}^{N} a_n(\theta)\, e^{\sigma_n \tau}\,[A_n(\tau) \cos(\omega_n\tau + \phi_n(\theta)) + B_n(\tau) \sin(\omega_n\tau + \phi_n(\theta))] \qquad (7)$$

where

$$A_n(\tau) = \int_0^{\tau} E^{e}(t)\, e^{-\sigma_n t} \cos \omega_n t\, dt \qquad (8)$$

$$B_n(\tau) = \int_0^{\tau} E^e(t)\, e^{-\sigma_n t} \sin \omega_n t \, dt \tag{9}$$

Since $A_n(\tau)$ and $B_n(\tau)$ are now functions of time, it is not possible to synthesize an $E^e(t)$ which can make those $A_n(\tau)$ and $B_n(\tau)$ vanish. Therefore, it is not possible to synthesize an excitation signal to excite a single-mode output signal in the early-time period of the output signal.

The next task is to synthesize the $E^e(t)$ for the single-mode excitation. There seems to be various ways to synthesize the $E^e(t)$, one of the ways is to construct $E^e(t)$ with a linear combination of the natural modes of the target (assuming the natural modes of the target are known). That is

$$E^e(t) = \sum_{n=1}^{N} e^{\sigma_m t} (b_m \cos \omega_m t + c_m \sin \omega_m t) \quad \text{for } 0 \le t \le T_e \tag{10}$$

where $\sigma_m + j\omega_m = s_m$ is the mth natural complex frequency, $b_m$ and $c_m$ are unknown coefficients to be determined, and $E^e(t) = 0$ outside the time domain of $0 \le t \le T_e$.

The substitution of eq. (10) in eqs. (5) and (6) leads to

$$A_n = \sum_{m=1}^{N} M_{nm}^1 \, b_m + \sum_{m=1}^{N} M_{nm}^2 \, c_m \tag{11}$$

$$B_n = \sum_{m=1}^{N} M_{nm}^3 \, b_m + \sum_{m=1}^{N} M_{nm}^4 \, c_m \tag{12}$$

where

$$\begin{bmatrix} M_{nm}^1 \\ M_{nm}^2 \\ M_{nm}^3 \\ M_{nm}^4 \end{bmatrix} = \int_0^{T_e} e^{-(\sigma_n - \sigma_m)t} \begin{bmatrix} \cos \omega_n t \cos \omega_m t \\ \cos \omega_n t \sin \omega_m t \\ \sin \omega_n t \cos \omega_m t \\ \sin \omega_n t \sin \omega_m t \end{bmatrix} dt \tag{13}$$

Equations (11) and (12) can be written into a matrix form as

$$\begin{bmatrix} A_n \\ B_n \end{bmatrix} = \begin{bmatrix} M^1_{nm} & M^2_{nm} \\ M^3_{nm} & M^4_{nm} \end{bmatrix} \begin{bmatrix} b_m \\ c_m \end{bmatrix} \tag{14}$$

or

$$\begin{bmatrix} b_m \\ c_m \end{bmatrix} = \begin{bmatrix} M^1_{nm} & M^2_{nm} \\ M^3_{nm} & M^4_{nm} \end{bmatrix}^{-1} \begin{bmatrix} A_n \\ B_n \end{bmatrix} \tag{15}$$

To synthesize an $E^e(t)$ for the jth mode excitation, we specify that $A_j = 1$ or $B_j = 1$ and let all other $A_n$ and $B_n$ go to zero in eq. (15). The unknown coefficients $b_m$ and $c_m$ can then be obtained immediately from eq. (15), and the required excitation signal $E^e(t)$ for the jth mode excitation is constructed based on eq. (10).

## 5. K-Pulse

We have recently initiated a study on the synthesis of an aspect-independent, excitation signal which will excite a target in such a way that it produces a return signal with zero late-time response. This signal was called Kill-pulse or K-pulse by Kennaugh [3] and initially studied by him. We aim to synthesize the K-pulse based on a similar approach we have been using. This approach is a modified version of that given in Section 4 and it is entirely different from the method used by Kennaugh [3].

A K-pulse, $E^e_k(t)$, by definition, will produce an output signal $E^o(\tau)$ which goes to zero after $\tau > T_e$. That is to demand that all $A_n$ and $B_n$ go to zero. Under this condition and based on eq. (14) of Section 4, it is obvious that non-trivial solutions for $b_m$ and $c_m$ exist only where the [M] matrix becomes singular, or the determinant $|M|$ vanishes. Since the elements of [M] matrix as given in eq. (13) of Section 4 are functions of the pulse duration

$T_e$, an effort was made to search numerically possible values for $T_e$ which make [M] matrix singular. It was concluded that no such $T_e$ exists with the matrix elements given in eq. (13). That implies that no K-pulse can be constructed with a linear combination of natural modes as expressed in eq. (10). However, if other basis functions, other than the natural modes, are used to construct a K-pulse, we may be able to find some optimum $T_e$'s which will make [M] matrix singular. Indeed this is the case when pulse functions are used to construct the K-pulse.

For example, let

$$E_k^e(t) = \sum_{m=1}^{2N} d_m P_m(t) \tag{16}$$

where

$$P_m(t) = \begin{cases} 1 & \text{for} \quad (m-1)\,\Delta T \leq t \leq m\Delta T \\ 0 & \text{otherwise} \end{cases}$$

$$\Delta T = T_e/2N$$

and $d_m$ is the unknown coefficient associated with $P_m(t)$ and to be determined based on the definition of the K-pulse. When $E_k^e(t)$ of eq. (16) is convolved with the radar return of eq. (1) of Section 4, the output signal in the late-time period becomes

$$\begin{aligned} E^o(\tau) &= \int_o^{T_e} E_k^e(t) \left[\sum_{n=1}^{N} a_n(\theta)\, e^{\sigma_n(\tau-t)} \cos(\omega_n(\tau-t) + \phi_n(\theta))\right] dt \\ &= \sum_{n=1}^{N} a_n(\theta)\, e^{\sigma_n\tau} \left[A_n^K \cos(\omega_n\tau + \phi_n(\theta)) + B_n^k \sin(\omega_n\tau + \phi_n(\theta))\right] \end{aligned} \tag{17}$$

where

$$A_n^k = \int_0^{T_e} E_k^e(t)\, e^{-\sigma_n t} \cos \omega_n t \, dt \tag{18}$$

$$B_n^k = \int_0^{T_e} E_k^e(t)\, e^{-\sigma_n t} \sin \omega_n t \, dt \tag{19}$$

Substituting eq. (16) in eqs. (18) and (19), we have

$$A_n^k = \sum_{m=1}^{2N} d_m M_{nm}^c \tag{20}$$

$$B_n^k = \sum_{m=1}^{2N} d_m M_{nm}^s \tag{21}$$

where

$$\begin{bmatrix} M_{nm}^c \\ M_{nm}^s \end{bmatrix} = \int_{(m-1)\Delta T}^{m\Delta T} e^{-\sigma_n t} \begin{bmatrix} \cos \omega_n t \\ \sin \omega_n t \end{bmatrix} dt \tag{22}$$

Eqs. (20) and (21) can be written in a matrix form as

$$\begin{bmatrix} A_n^k \\ B_n^k \end{bmatrix} = \begin{bmatrix} M_{nm}^c \\ M_{nm}^s \end{bmatrix} \begin{bmatrix} d_m \end{bmatrix} \tag{23}$$

where n = 1, 2, --- N, and m = 1, 2, --- 2N. The matrix $\begin{bmatrix} M_{nm}^c \\ M_{nm}^s \end{bmatrix}$ is a square matrix which elements are quite different from that of [M] matrix appeared in eqs. (14) and (15) of Section 4.

If $E_k^e(t)$ is a K-pulse, all $A_n^k$ and $B_n^k$ should vanish. Now for $E_k^e(t)$ to exist, there should be non-trivial solutions for $d_m$. That is to have a singular $\begin{bmatrix} M_{nm}^c \\ M_{mn}^s \end{bmatrix}$ matrix. Since the elements of this matrix are also functions of the pulse duration $T_e$, a numerical search for optimum $T_e$'s which make the matrix singular was conducted. The first two optimum values for $T_e$ were found to be

$$T_e = 2.15\ (L/c) \text{ and } 4.12\ (L/c)$$

Once the optimum $T_e$ is found, the elements of the matrix, $M_{nm}^c$ and $M_{nm}^s$, are easily calculated. After that the values of $d_m$ are determined from a set of homogeneous simultaneous equations represented by eq. (23) when $A_n^k$ and $B_n^k$ are set to zero.

A numerical example is given in Fig. 13 where the K-pulse for a thin wire with (L/a = 200, L = length, a = radius) and $T_e$ = 2.15 (L/c) is shown. Only the first ten natural modes of the target were considered. This K-pulse is compared with Kennaugh's K-pulse in the same figure. These two K-pulses are very similar with a main difference that our K-pulse has a finite pulse duration of 2.15 (L/c) while Kennaugh's K-pulse has a tail part of infinite duration.

Another approach to synthesize a K-pulse is given below. Suppose we construct the K-pulse with a linear combination of natural modes of the target and a properly chosen function:

$$E_k^e(t) = \sum_{m=1}^{N} e^{\sigma_m t} (b_m \cos \omega_m t + c_m \sin \omega_m t) + K(t) \tag{24}$$

The first part of the r.h.s. of eq. (24) represents the sum of natural modes with unknown coefficients $b_m$ and $c_m$. The K(t) function in the r.h.s. of eq. (24) is a properly chosen function.

If eq. (24) is substituted in eqs. (18) and (19), $A_n^k$ and $B_n^k$ become

$$A_n^k = \sum_{m=1}^{N} M_{nm}^1 b_m + \sum_{m=1}^{N} M_{nm}^2 c_m + K_n^c \tag{25}$$

$$B_n^k = \sum_{m=1}^{N} M_{nm}^3 b_m + \sum_{m=1}^{N} M_{nm}^4 c_m + K_n^s \tag{26}$$

where $M_{nm}^1$, $M_{nm}^2$, $M_{nm}^3$ and $M_{nm}^4$ are the same matrix elements as that given in eq. (13) of Section 4. $K_n^c$ and $K_n^s$ are newly defined as

$$\begin{bmatrix} K_n^c \\ K_n^s \end{bmatrix} = \int_0^{T_e} K(t)\, e^{-\sigma_n t} \begin{bmatrix} \cos \omega_n t \\ \sin \omega_n t \end{bmatrix} dt \tag{27}$$

Eqs. (25) and (26) can be combined to be

$$\begin{bmatrix} A_n^k \\ B_n^k \end{bmatrix} = \begin{bmatrix} M_{nm}^1 & M_{nm}^2 \\ M_{nm}^3 & M_{nm}^4 \end{bmatrix} \begin{bmatrix} b_m \\ c_m \end{bmatrix} + \begin{bmatrix} K_n^c \\ K_n^s \end{bmatrix} \tag{28}$$

For a K-pulse, $A_n^k$ and $B_n^k$ are zero. That is

$$\begin{bmatrix} M_{nm}^1 & M_{nm}^2 \\ M_{nm}^3 & M_{nm}^4 \end{bmatrix} \begin{bmatrix} b_m \\ c_m \end{bmatrix} = - \begin{bmatrix} K_n^c \\ K_n^s \end{bmatrix} \tag{29}$$

or

$$\begin{bmatrix} b_m \\ c_m \end{bmatrix} = - \begin{bmatrix} M_{nm}^1 & M_{nm}^2 \\ M_{nm}^3 & M_{nm}^4 \end{bmatrix}^{-1} \begin{bmatrix} K_n^c \\ K_n^s \end{bmatrix} \tag{30}$$

Thus, the unknown coefficients for the natural modes needed to construct the K-pulse are determined provided a proper K(t) function is assigned.

For example, let's find the K-pulse for the same thin wire target as that of fig. 13, and assume that

$$K(t) = 1 \quad \text{for } 0 \le t \le T_e$$

$$T_e = T_1 = 2.16\ (L/c)$$

$$N = 10 \text{ (first ten natural modes)}$$

The K-pulse can then be expressed as

$$E_k^e(t) = \sum_{m=1}^{10} e^{\sigma_m t} (b_m \cos \omega_m t + c_m \sin \omega_m t) + 1 \qquad \text{for } 0 \le t \le T_e \tag{31}$$

The waveform of this K-pulse is shown in fig. 14 in comparison with Kennaugh's K-pulse. There is a strong resembrance between these two K-pulses. The main difference is that our K-pulse has a finite duration while Kennaugh's K-pulse is of infinite duration.

The study on the K-pulse will be continued in the future. We plan to study the convergence of the K-pulse when more natural modes are considered, and the optimum pulse duration.

6. Experimental Setup for the Radar Waveform Synthesis Method

We have made a good progress in the construction of the experimental set-up. A large ground plane composed of nine 4' x 8' modules has been constructed. A biconical transmitting antenna with a length of 8 feet and a half-angle of 8° has been fabricated. A short monopole has been used as the receiving probe. The basic experimental arrangement including relevant pieces of equipment is shown in Figure 15. The biconial transmitting antenna is driven by a pulse generator through a delay-line. A small portion of the output of the pulse generator is taken, through a home-made "takeoff tee", and used to trigger the sampling scope. The transmitted pulse and the scattered field from the target are received by the short monopole probe. The received signal by the probe represents essentially the time-derivatives of the transmitted pulse and the scattered field from the target. This received signal is fed to the sampling scope. The receives signal from the probe is also integrated by an operational-amplifier to recover approximately the original waveforms of the transmitted pulse and the scattered field from the target. The received signal from the probe and the integrated result of it can be recorded in a x-y plotter.

Some preliminary experimental results are shown in Figures 16 to 17. Figure 16 shows the received signal by the probe with and without the presence of a square pipe target. The pulse in the left is due to the transmitted pulse and that in the right is due to the scattered field from the target. It is evident that this received signal by the probe represents the time-derivatives of the transmitted pulse and the scattered field from the target. Figure 17 shows the integrated result of the received signal by the probe

that is shown in Figure 16. This result represents approximately the original waveforms of the transmitted pulse and the scattered field from the target.

The experimental arrangement and experimental results shown here are only preliminary. We will make efforts to improve the experimental system, and solve some encountered problems which include the clutter, the drifting of the operational-amplifier and the performance of the receiving probe.

## 7. Future Plans

The following topics will receive major attention in the future:

(1) Experimental study.

(2) Alternative scheme of producing the single-mode backscatters using a computer.

(3) K-pulse

(4) Two skew coupled wires.

(5) A cross-wire system.

(6) An aircraft modeled with elements of cylinders.

## 8. Personnel

The following personnel have participated in this research program.

(1) Kun-Mu Chen, Professor and principal investigator.

(2) Dennis P. Nyquist, Professor and senior investigator.

(3) Byron Drachman, Associate Professor of mathematics, consultant.

(4) Che-I Chuang, Graduate Assistant.

(5) Lance Webb, Graduate Assistant.

## 9. Publication

The results of this research program have been published in the following papers or presented in the following meetings.

1. K.M. Chen, N.P. Nyquist, D. Westmoreland, C. I. Chuang, and B. Drachman, "Radar waveform synthesis for single-mode scattering by a thin cylinder and application for target discrimination," to appear in IEEE Trans. on Antennas and Propagation, Sept. 1982.

2. K.M. Chen and D. Westmoreland, "Radar waveform synthesis for exciting single-mode backscatters from a sphere and application for target discrimination," to appear in Radio Science, 1982.

3. C.I. Chuang, D.P. Nyquist, K.M. Chen and B.C. Drachman, "Incident waveform synthesis for monomode scattering by an infinite cylinder and its application for target identification," submitted to IEEE Trans. on Aerospace and Electronic Systems.

4. C.I. Chuang, D.P. Nyquist, K.M. Chen and B.C. Drachman, "Incident-waveform synthesis for monomode scattering by an infinite cylinder and its application for target discrimination," presented at 1982 National Radio Science Meeting, Boulder, Colorado, Jan. 13-15, 1982.

5. C.I. Chuang, D.P. Nyquist and K.M. Chen, "Excitation of single-mode backscatters from two skew coupled wires," presented at 1982 National Radio Science Meeting, Boulder, Colorado, Jan. 13-15, 1982.

References

1. K.M. Chen, D.P. Nyquist, D. Westmoreland, C. I. Chuang, and B. Drachman, "Radar waveform synthesis for single-mode scattering by a thin cylinder and application for target discrimination," to appear in IEEE Trans. on Antennas and Propagation, Sept. 1982.

2. K.M. Chen and D. Westmoreland, "Radar waveform synthesis for exciting single-mode backscatters from a sphere and application for target discrimination," to appear in Radio Science, 1982.

3. E.M. Kennaugh, "The K-pulse concept," IEEE Trans. on Antennas and Propagation, AP-29, No. 2, 327-331, March 1981.

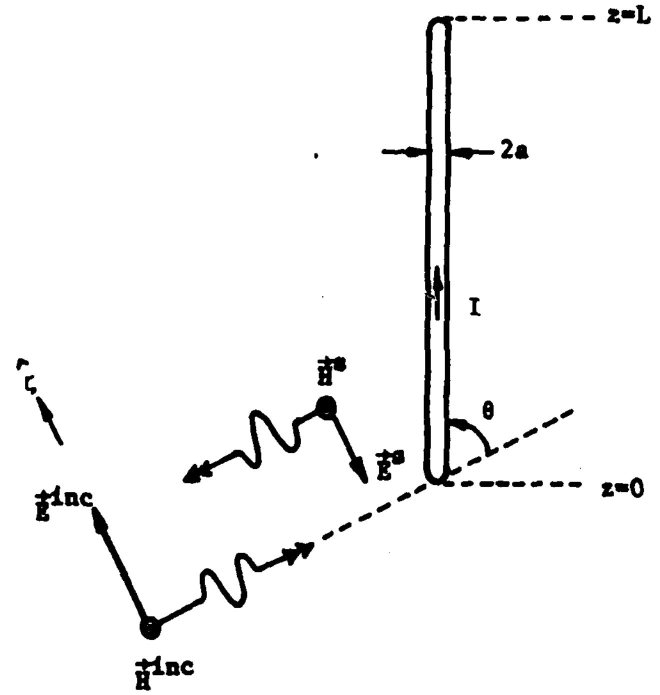


fig. 1. A thin wire is illuminated by a radar signal at an oblique angle.

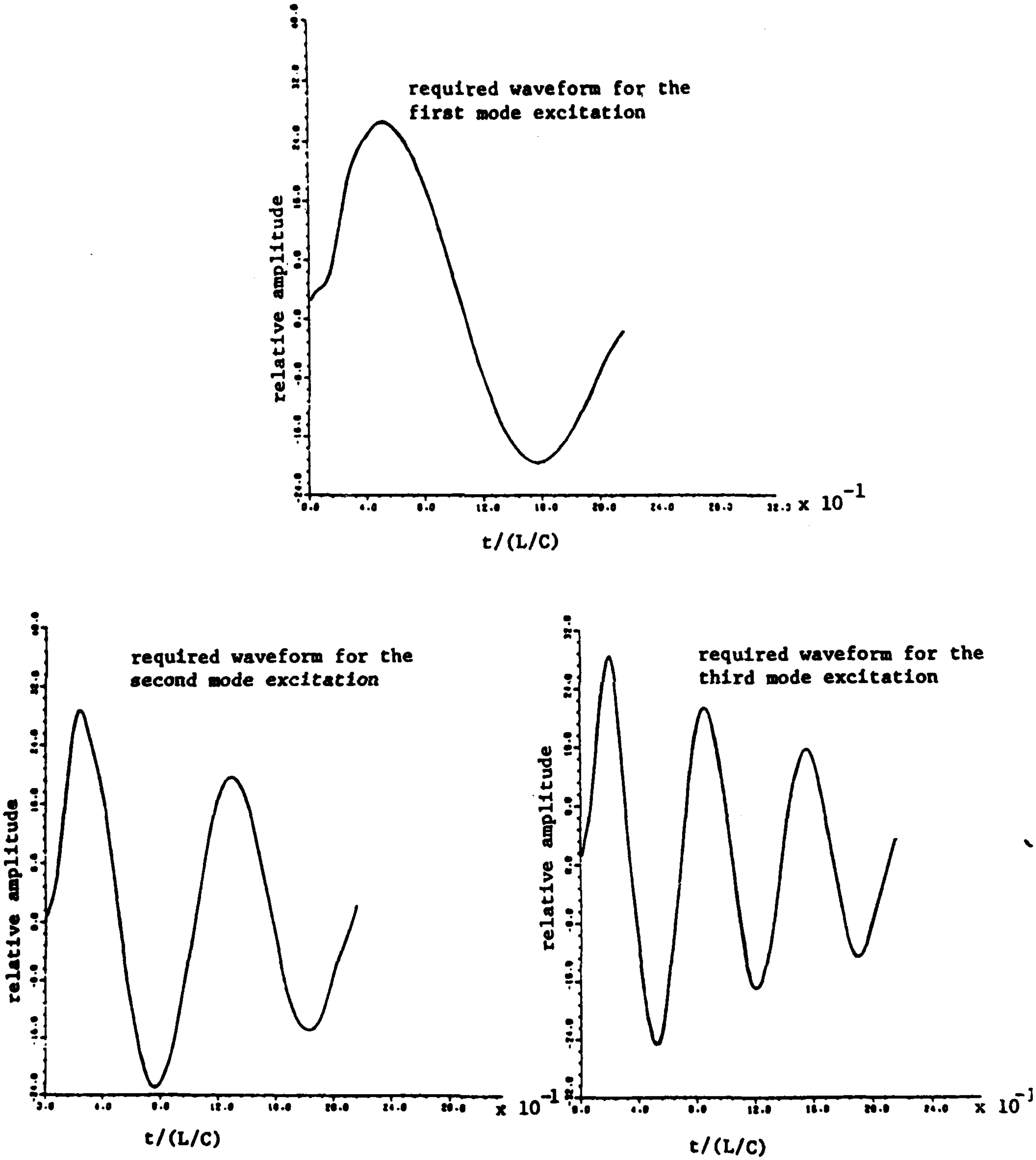


fig. 2. Required waveforms for the incident radar signal to excite a return radar signal from an arbitrarily oriented wire containing only the first, the second and the third natural mode, respectively.

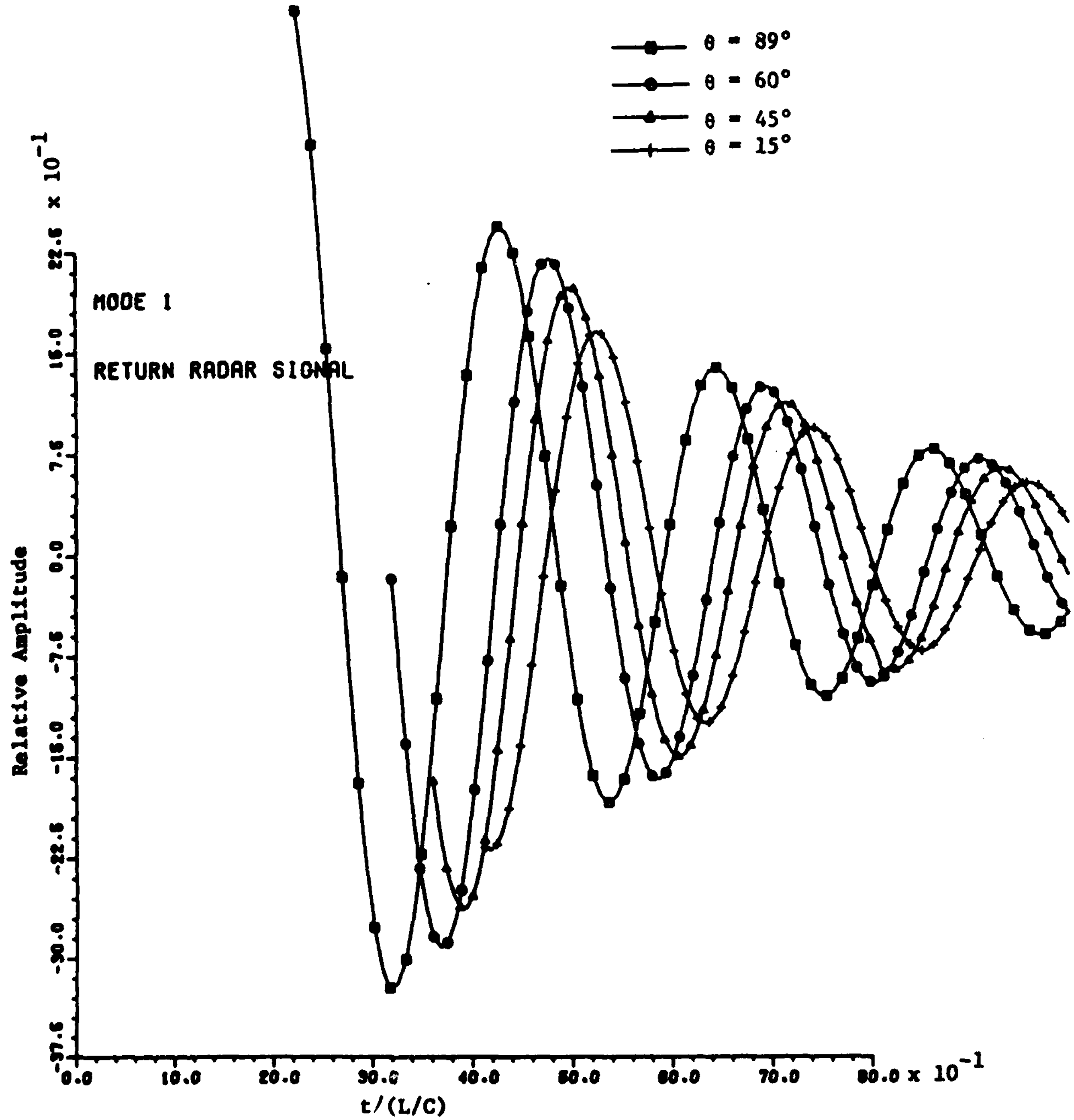


fig. 3. Return radar signals from a wire oriented at various angles, $\theta=15°$, $45°$, $60°$ and $89°$, when it is illuminated by the incident radar signal which is synthesized for the first mode excitation.

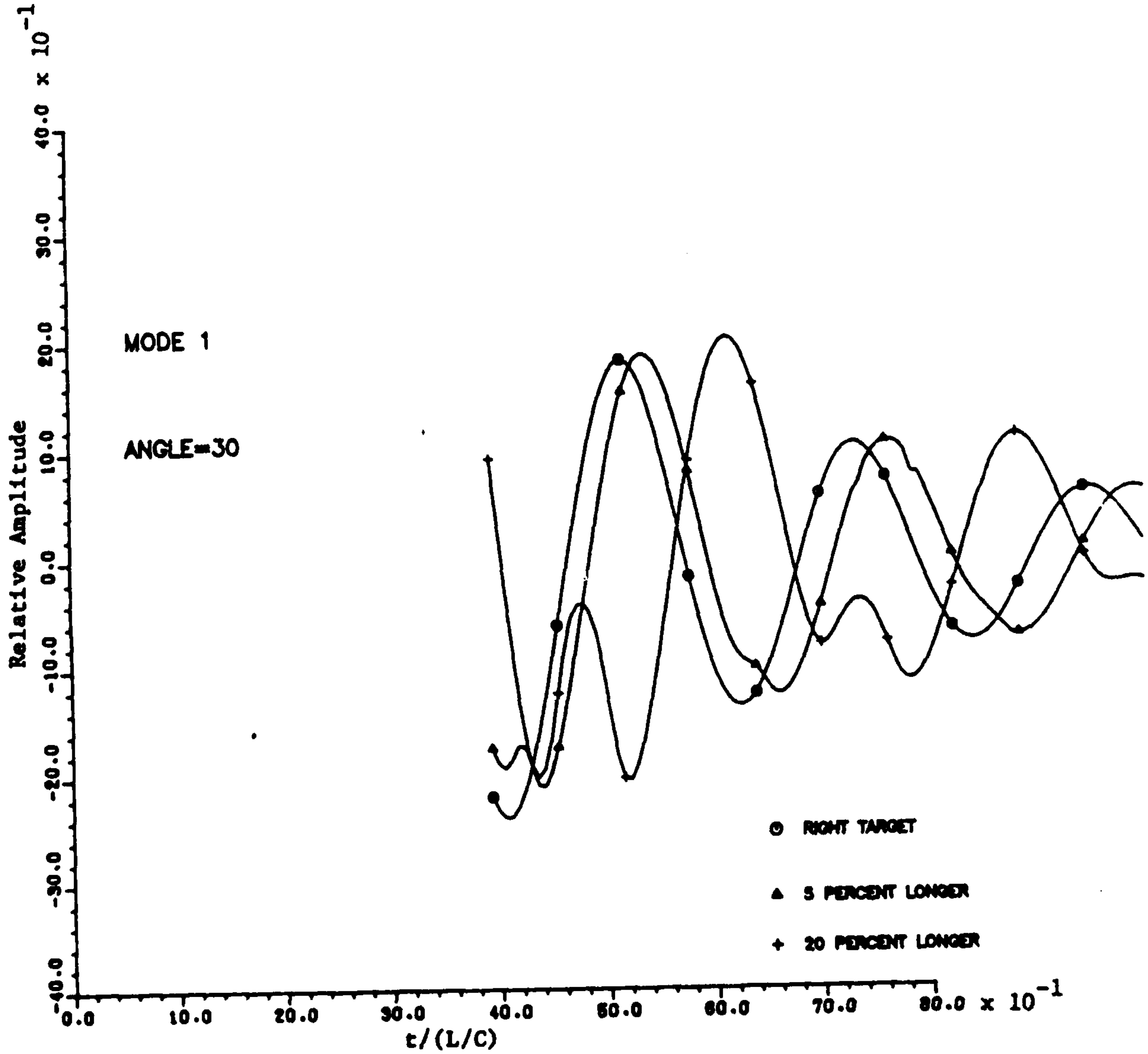


fig. 4 Return radar signals from three targets, the right target (wire), a wire 5% longer than the right target and a wire 20% longer, when they are illuminated at 30° aspect angle by the incident radar signal which is synthesized for exciting the first natural mode of the right target.

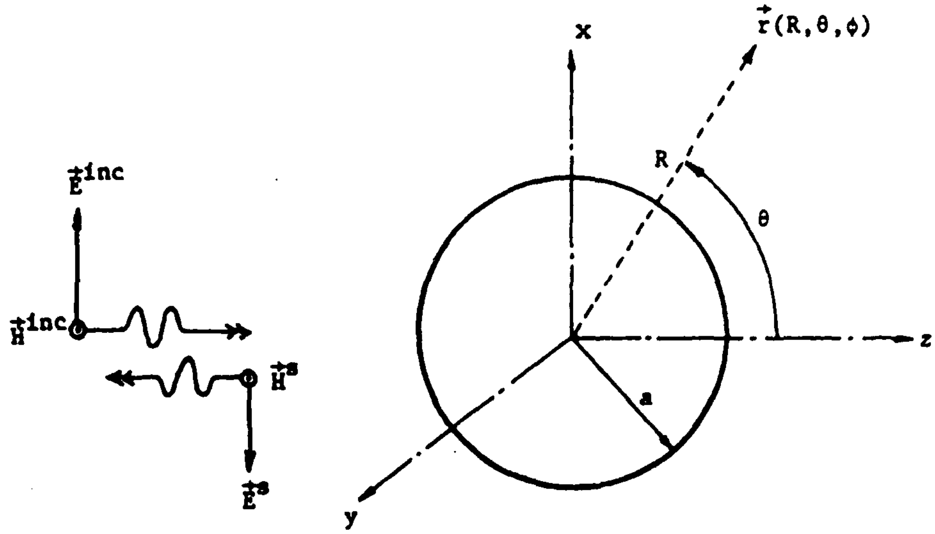


fig. 5 A perfectly conducting sphere of radius a is illuminated by a radar signal propagating in the + z-direction.

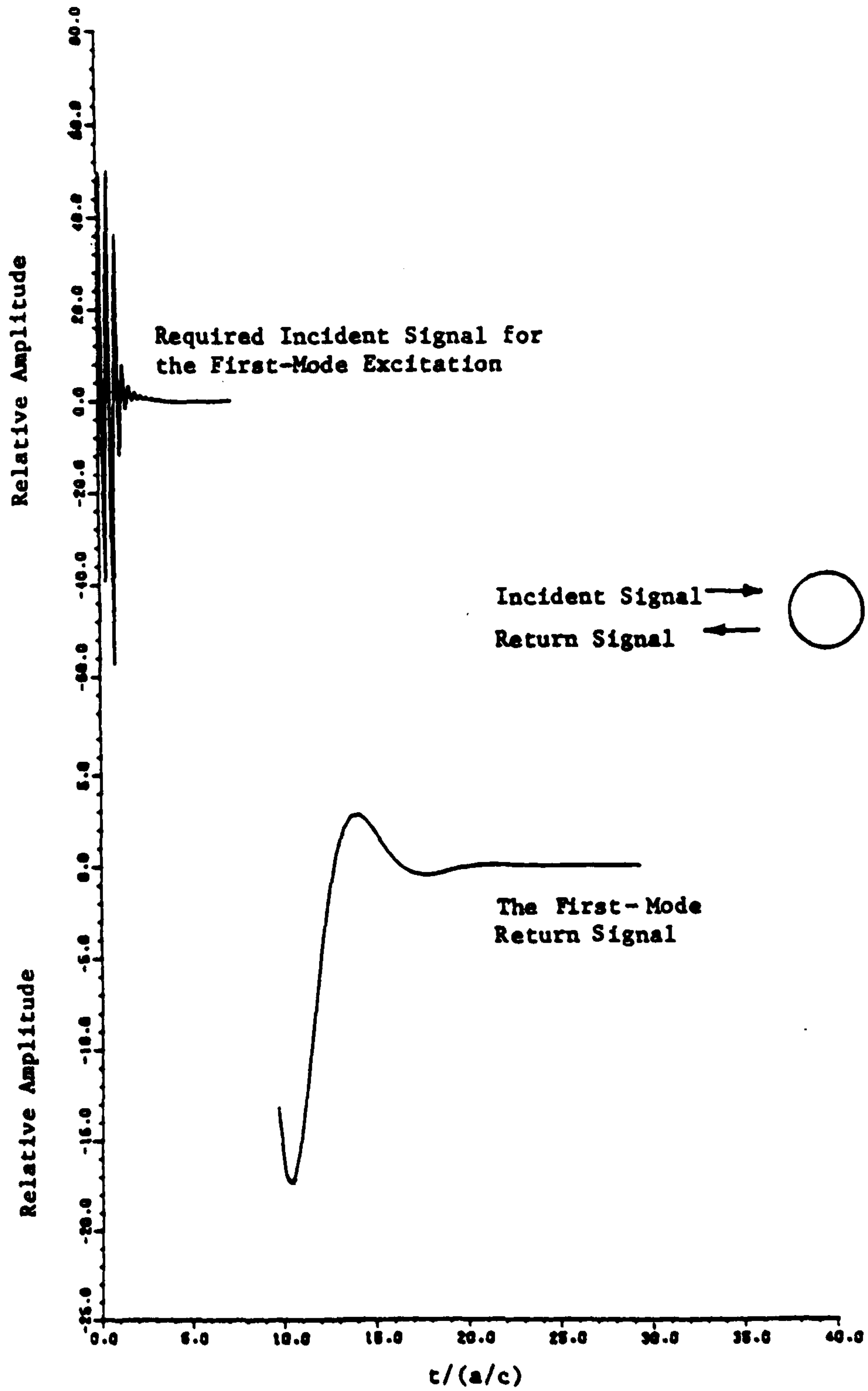


fig. 6 The required incident signal for exciting the first natural mode of a sphere, and the return signal which contains only the first natural mode.

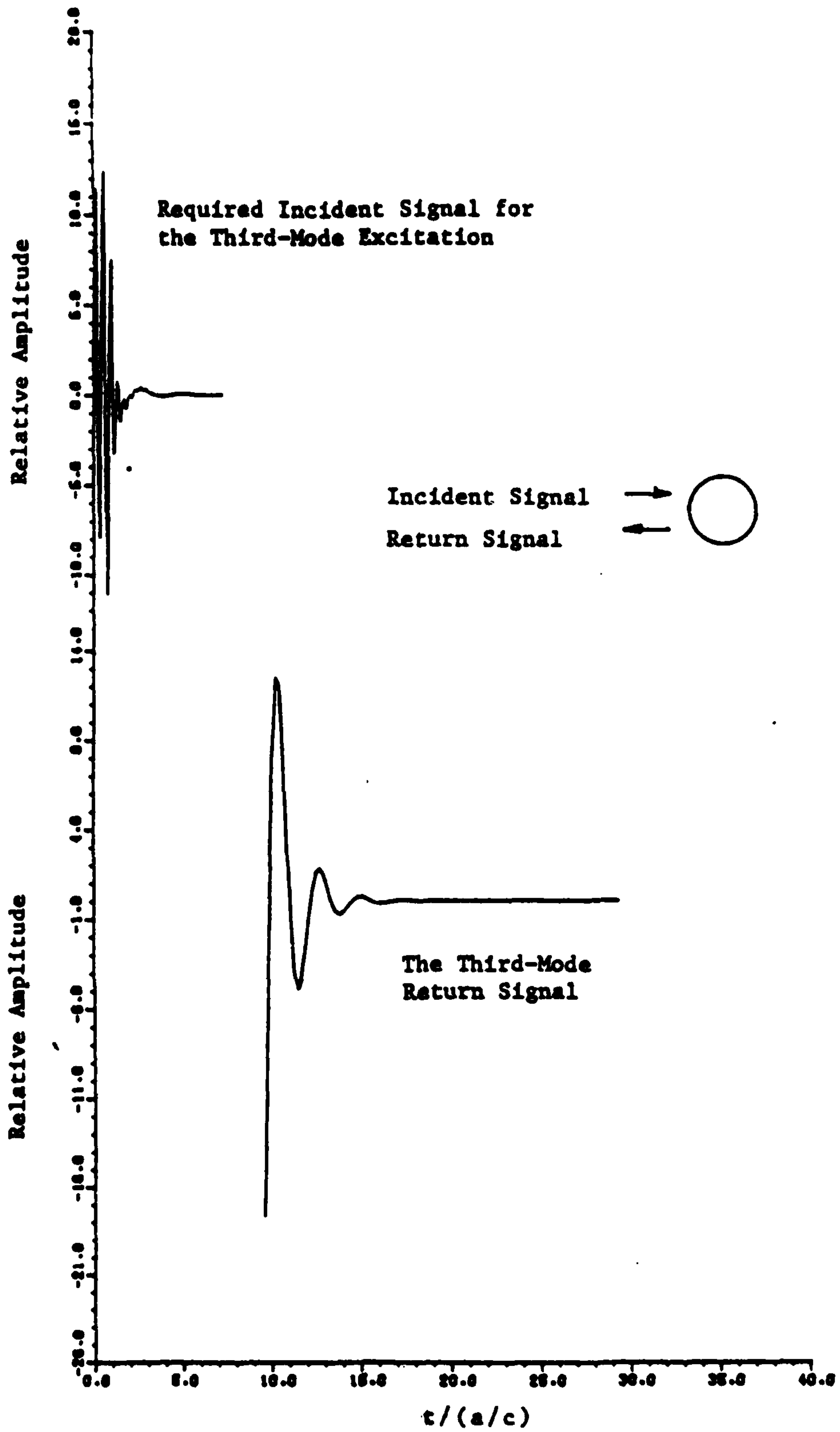


fig. 7 The required incident signal for exciting the third natural mode of a sphere, and the return signal which contains only the third natural mode.

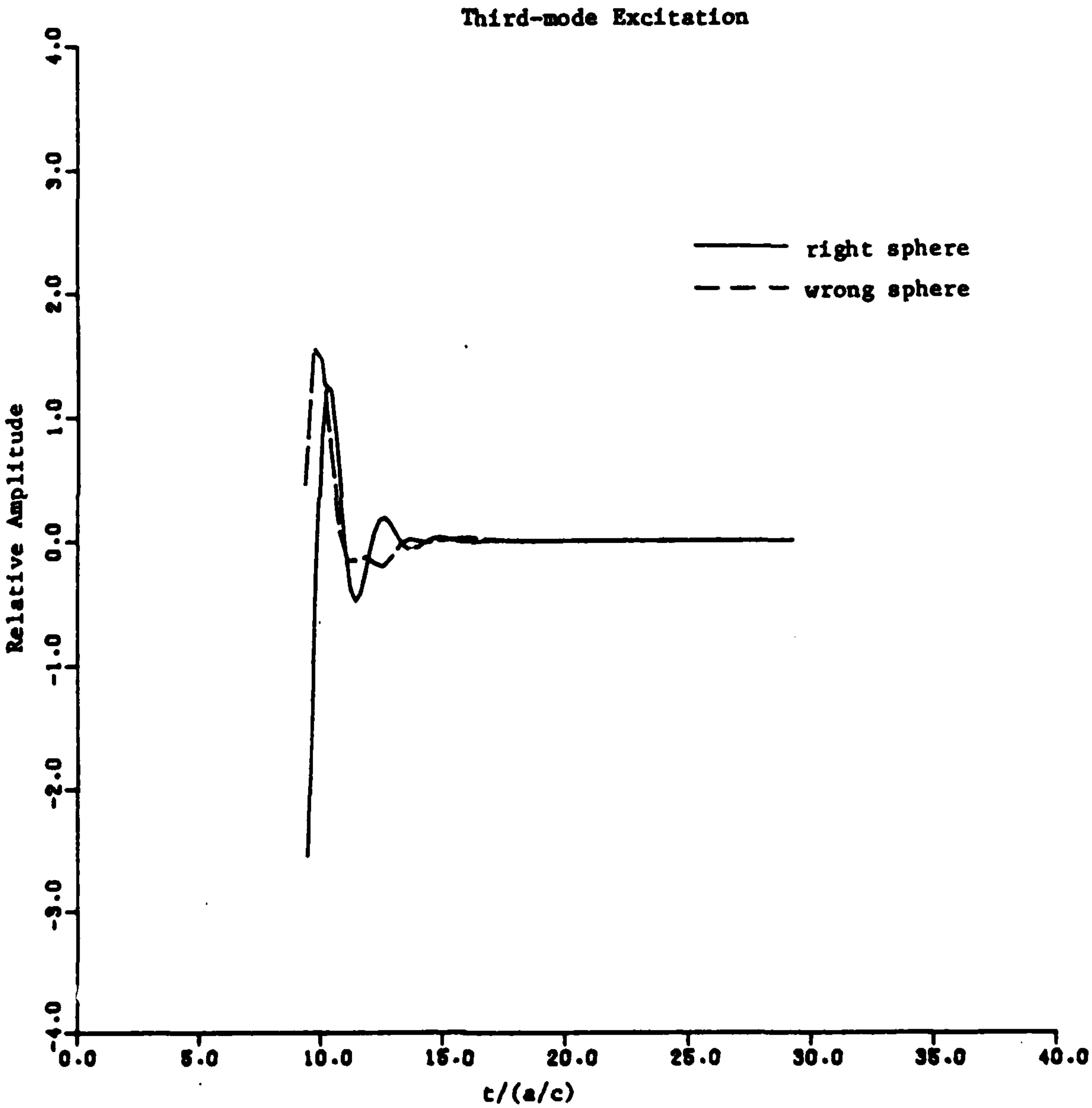


fig. 8 The return signals from the right sphere and a wrong sphere which radius is 10% smaller than that of the right sphere when they are illuminated by the incident signal synthesized to excite the third natural mode of the right sphere.

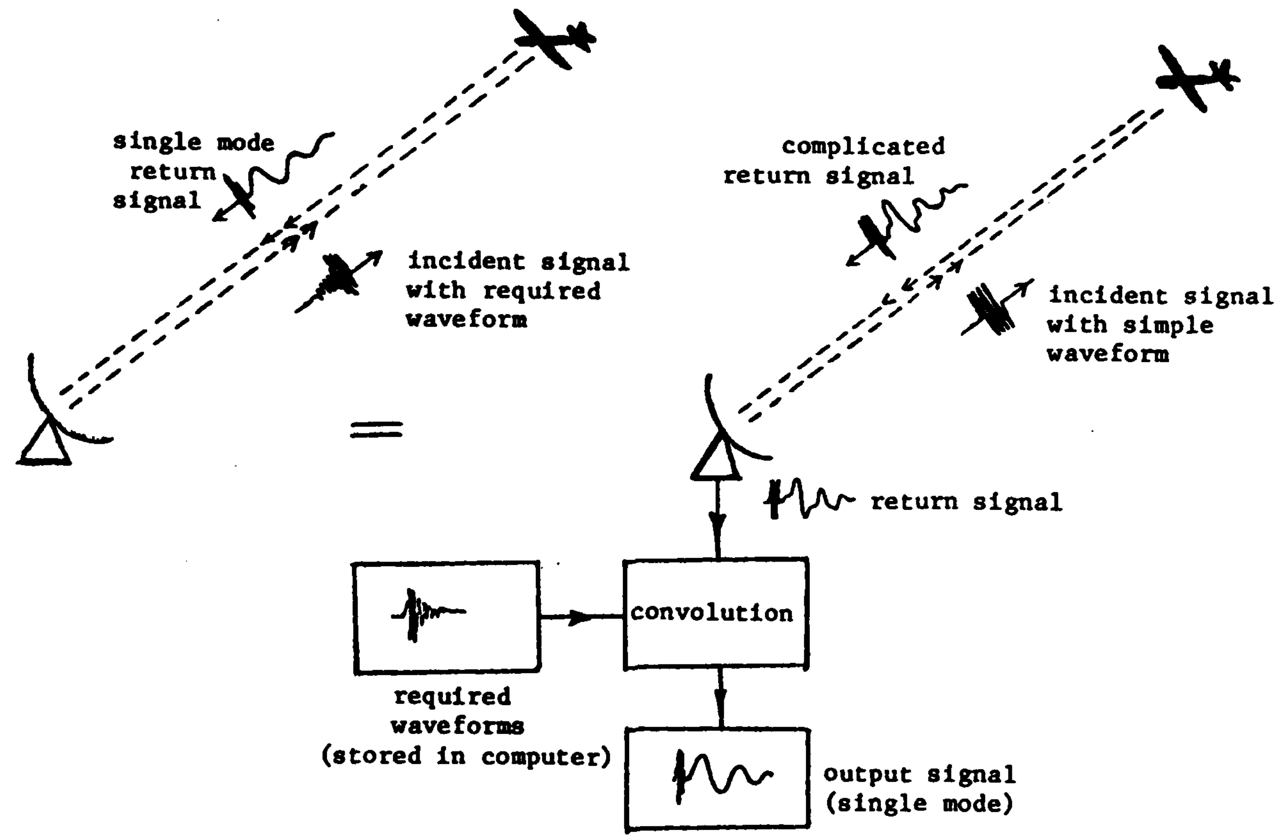


fig. 9 Two equivalent arrangements for target discrimination

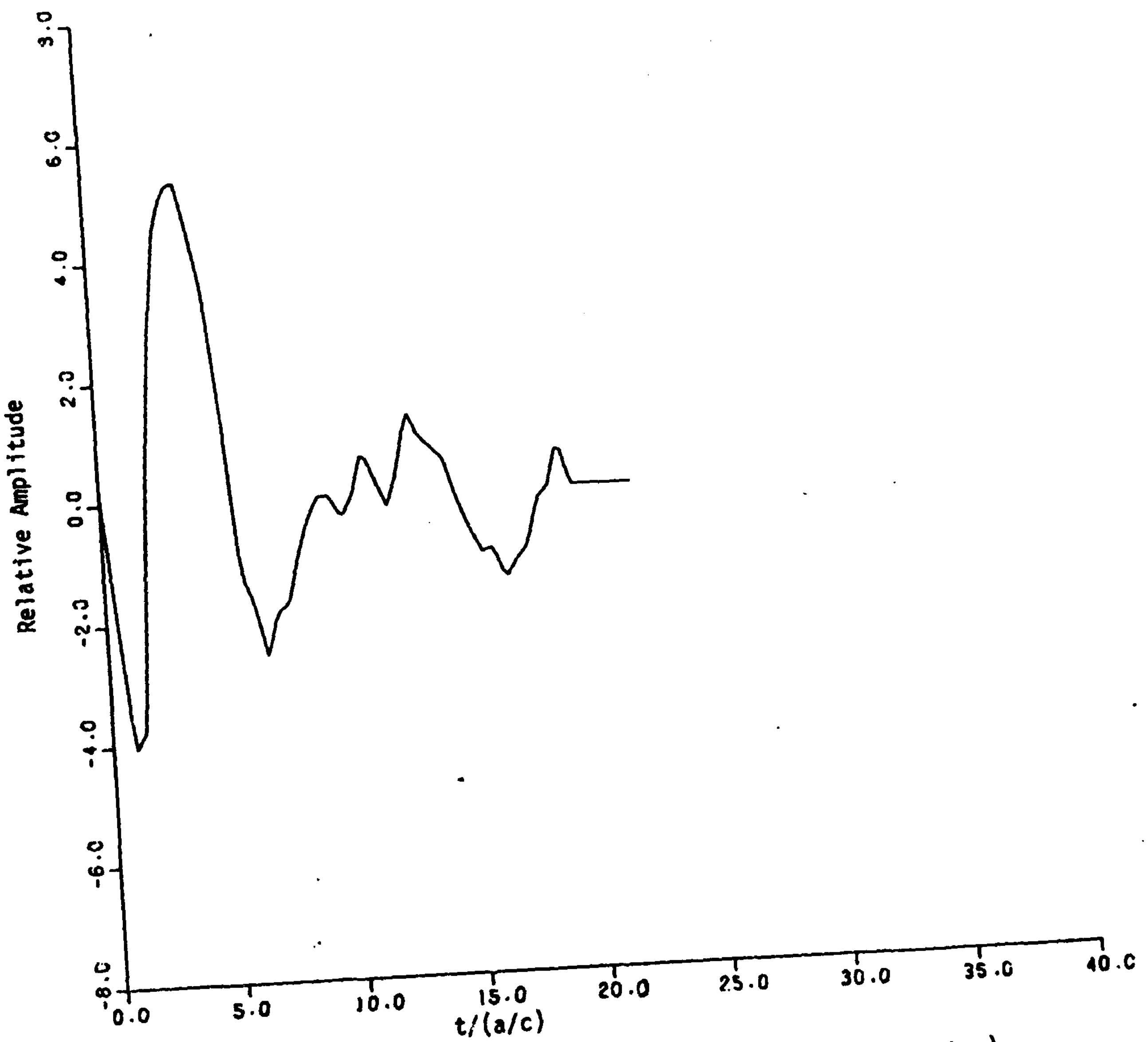


fig. 10 Bistatic response or impulse response of 5 inch (diameter) sphere measured by Dr. Bruce Hollmann.

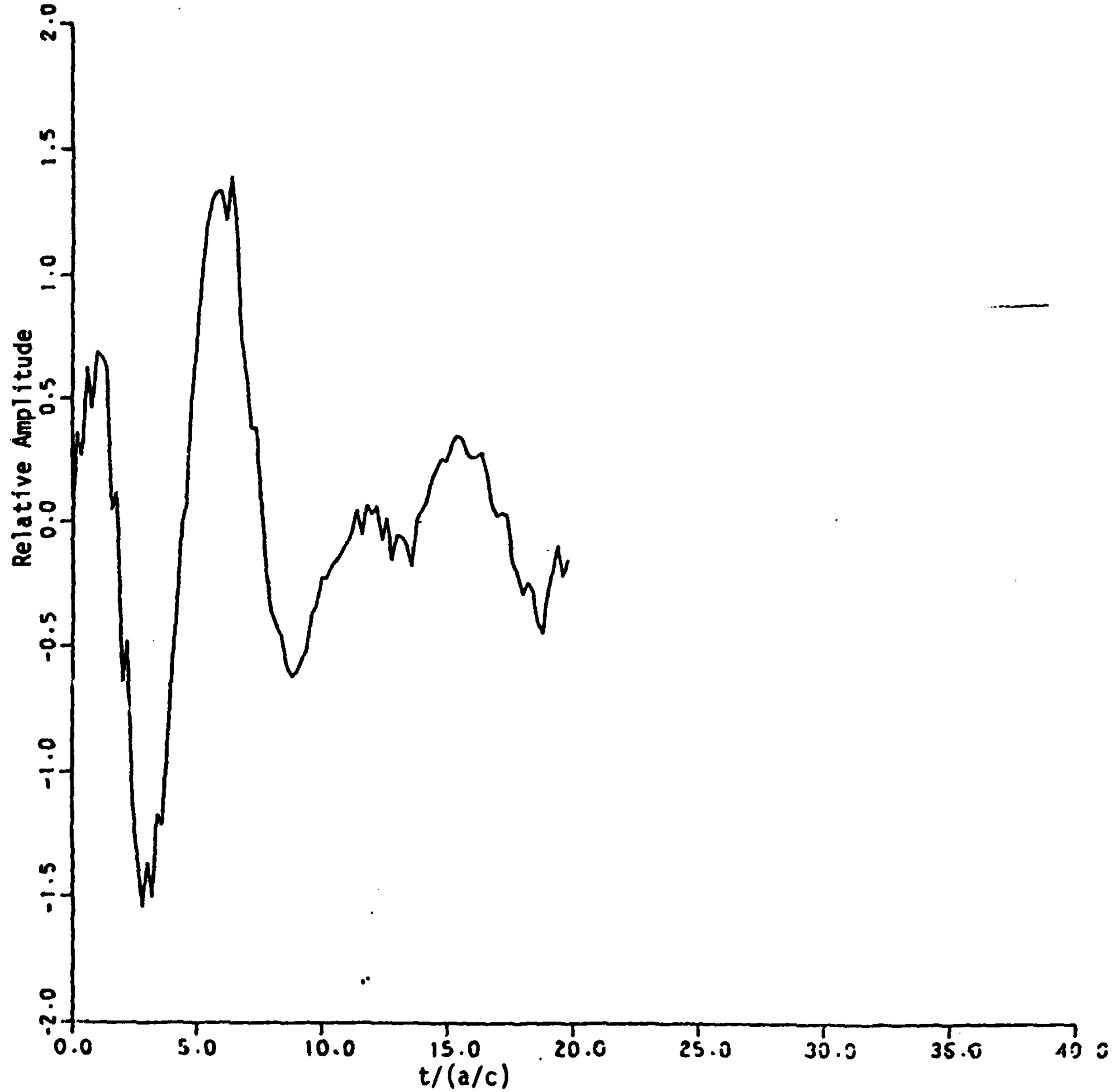


fig. 11 Output signal produced by convoluting the bistatic response of the sphere with the required radar signals for the first-mode excitation.

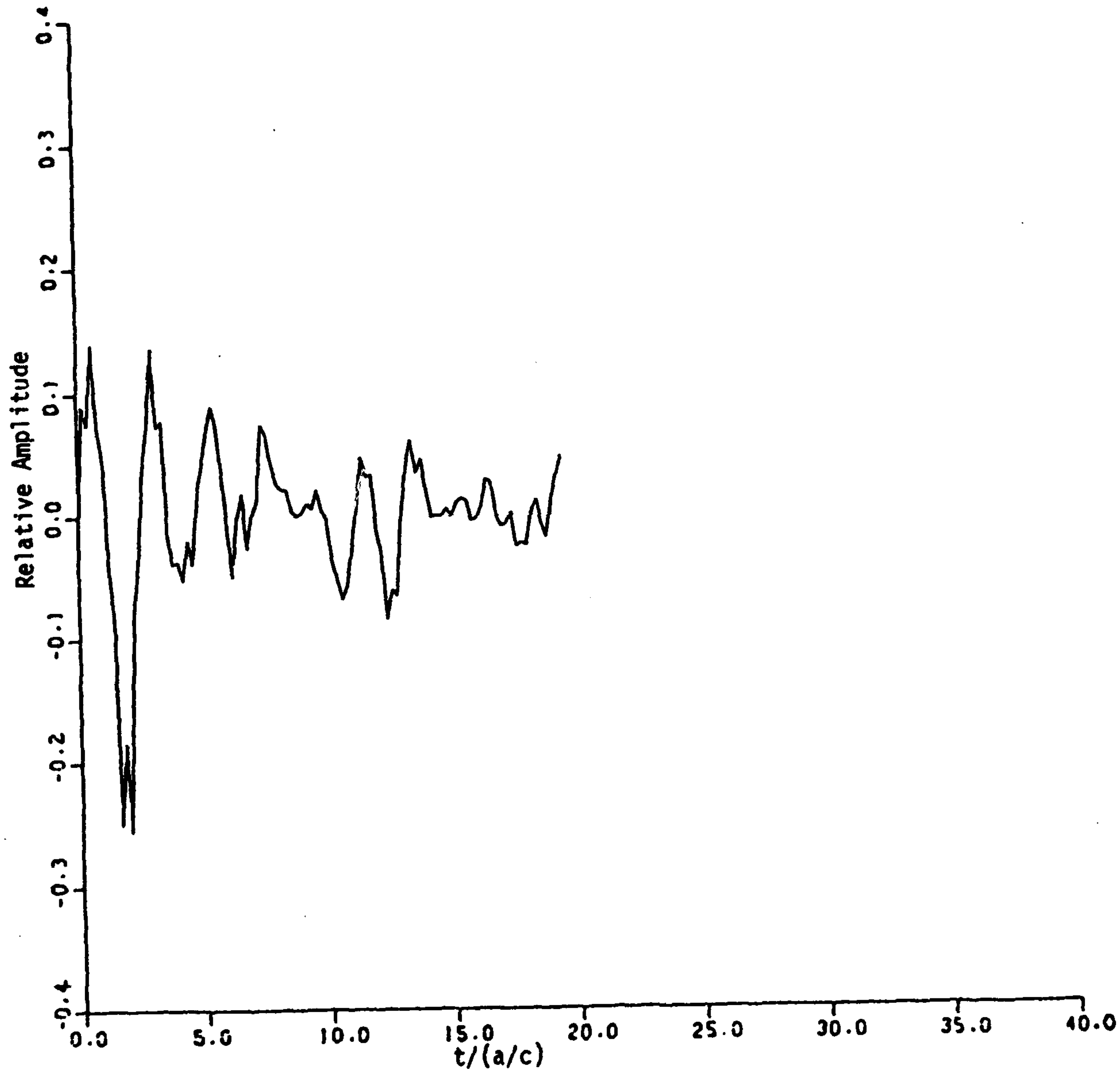


fig. 12 Output signal produced by convoluting the bistatic response of the sphere with the required radar signal for the third-mode excitation.

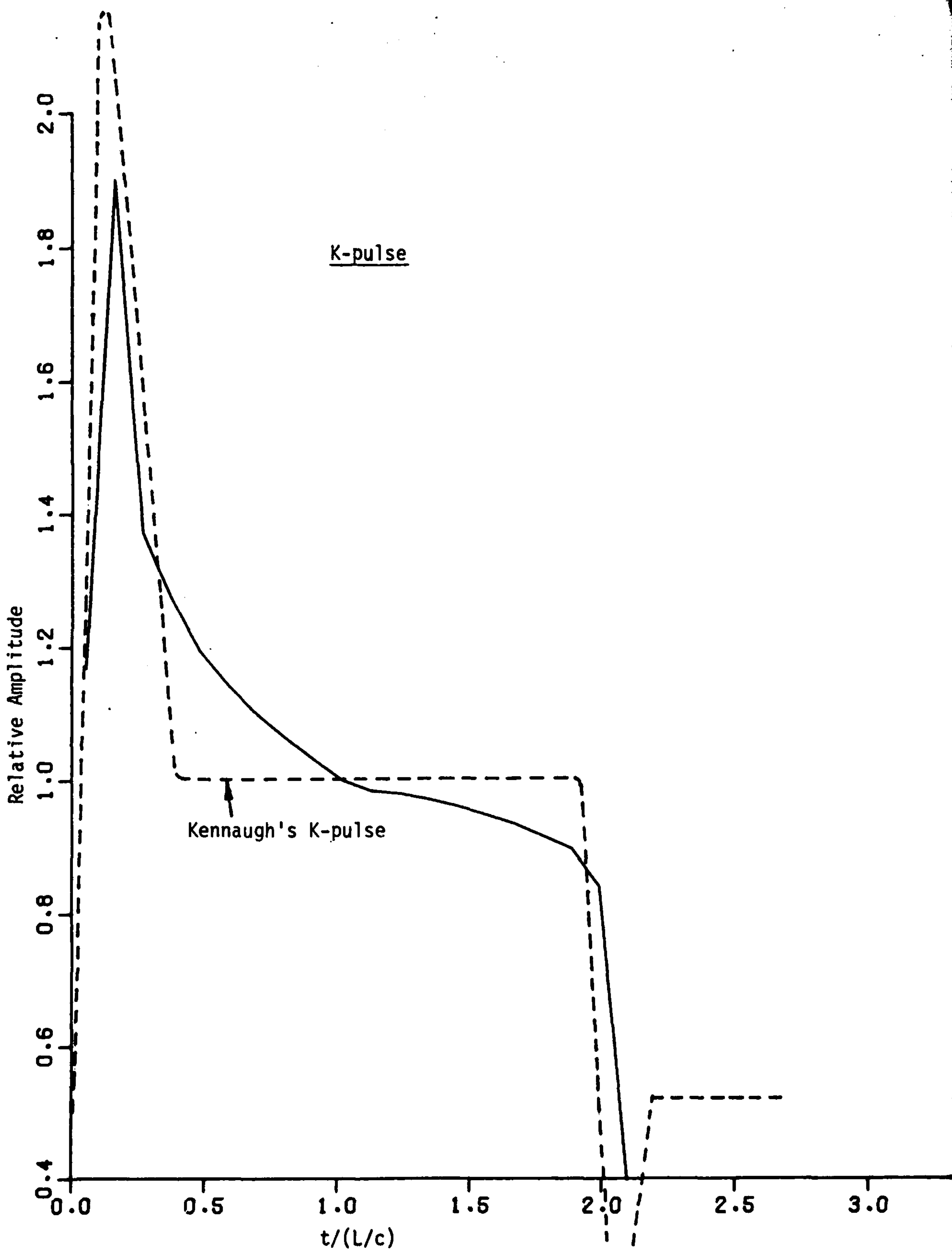


Fig. 13 K-pulse for an arbitrarily oriented thin wire (L/a = 200).

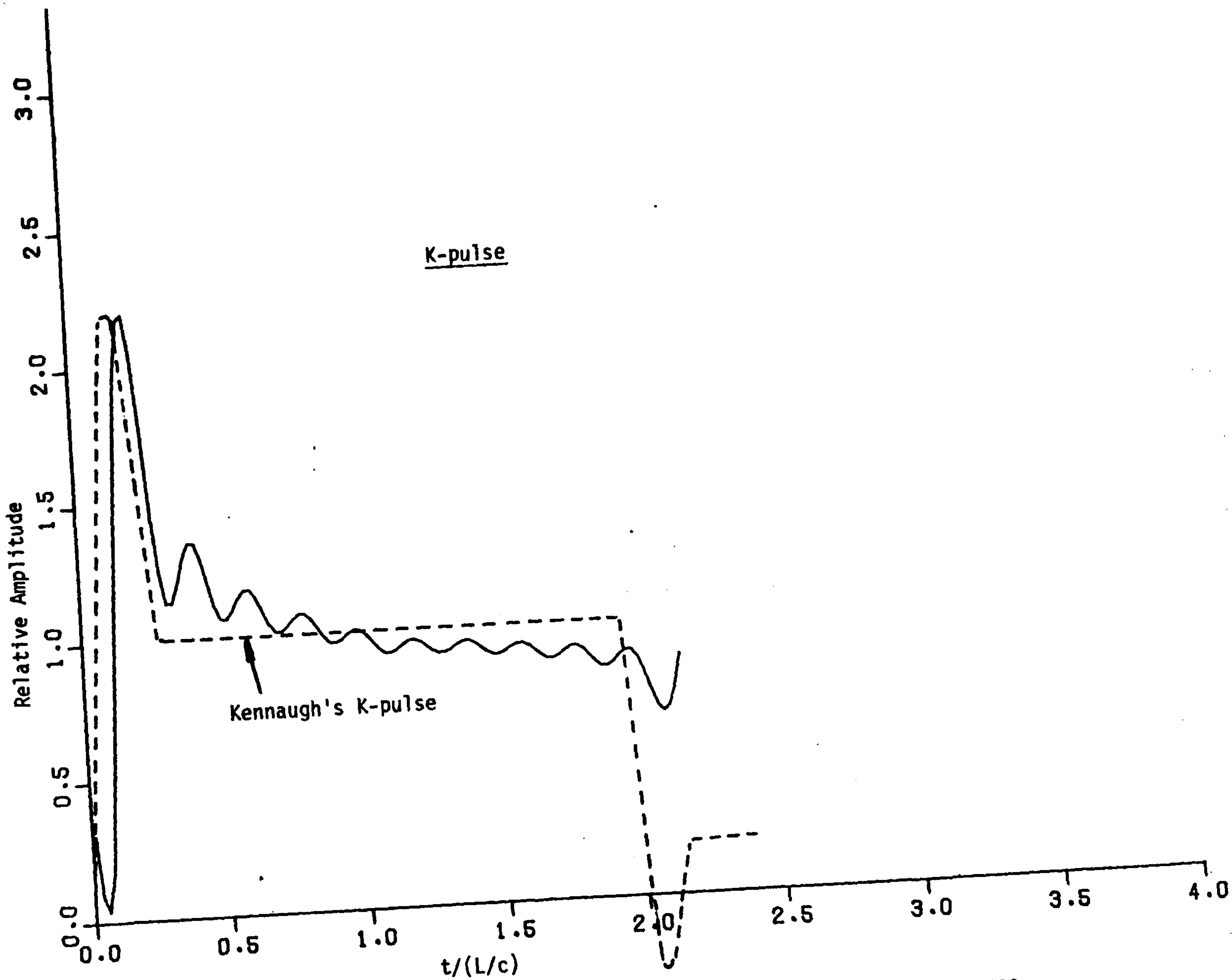


Fig. 14 Required waveform of the excitation signal to produce a zero late-time response from an arbitrarily oriented wire with (L/a = 200).

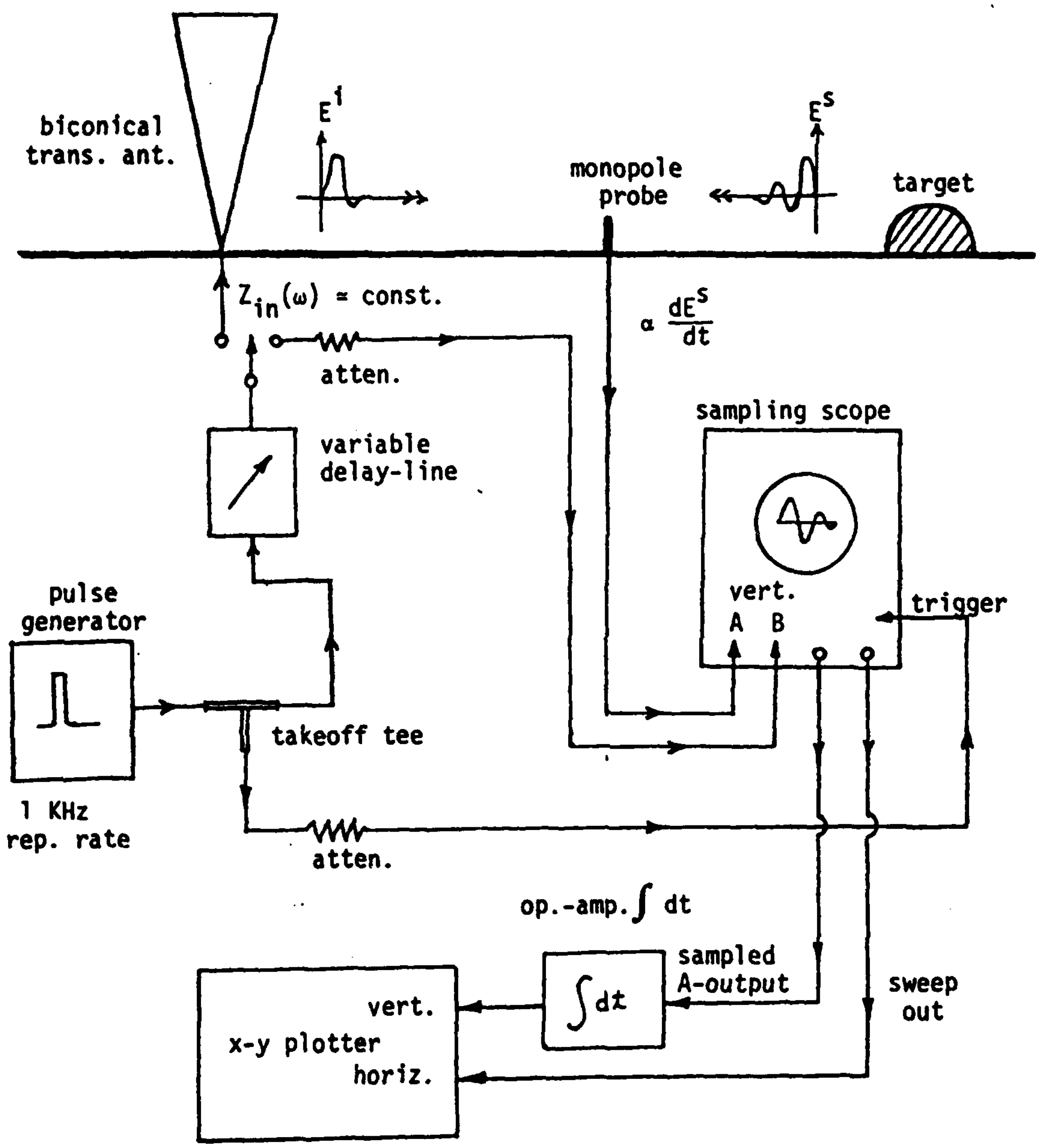


Fig. 15 Basic experimental arrangement for measuring the scattered fields from radar targets.

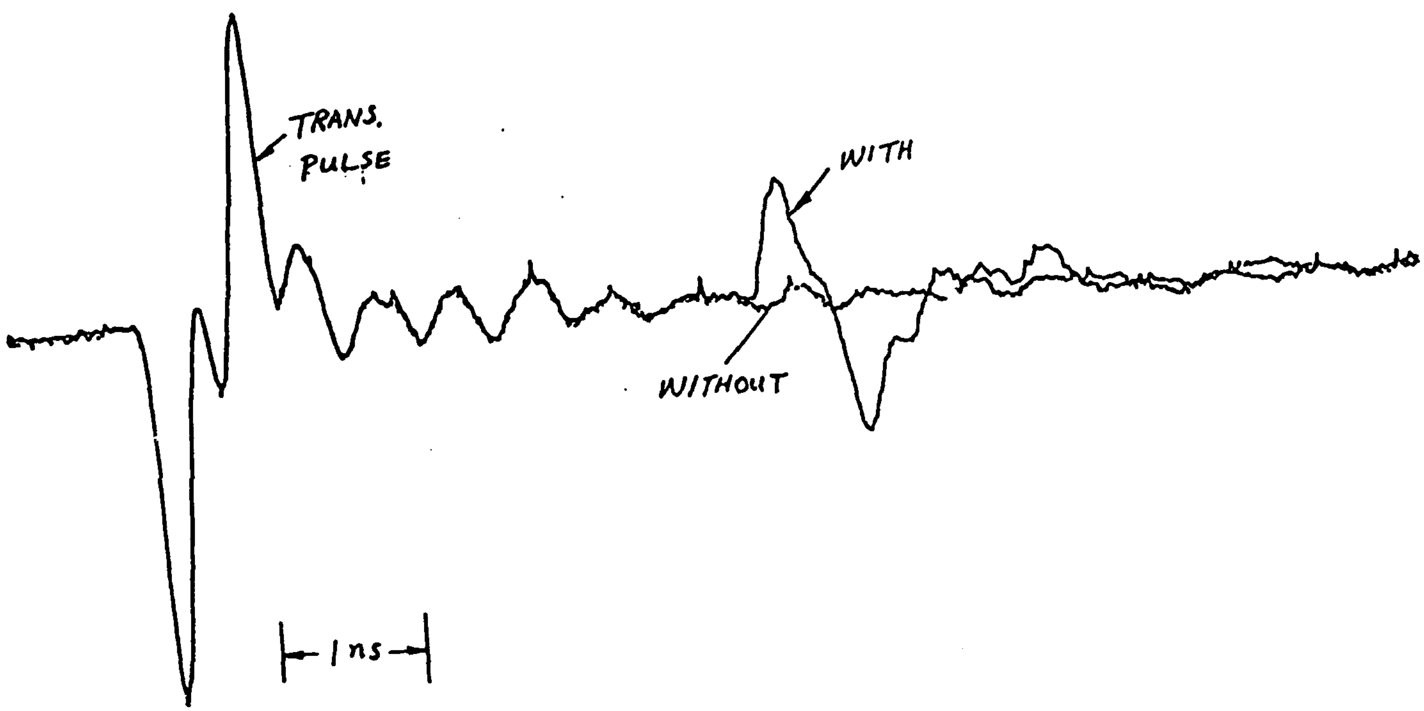


Fig. 16  Received signals by a short monopole probe with and without the presence of a square pipe target.

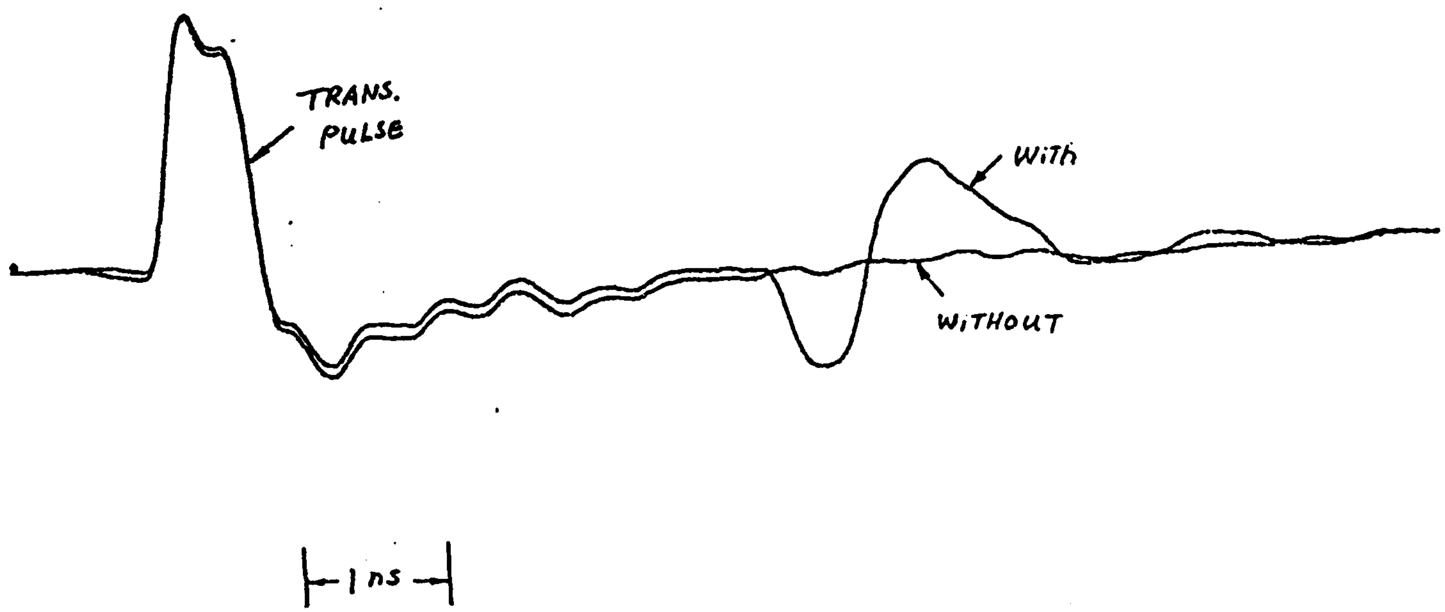


Fig. 17 Integrated results of the signals received by the probe as that shown in fig. 14.

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